Production of a ^{76}Kr Radioactive Ion Beam using a Batch Mode Method[1]

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A batch mode process has been used to produce a ^{76}Kr ($T_{1/2}$ = 14.8 h) radioactive ion beam using the 88-Inch Cyclotron. This development was motivated by the desire to extend towards N=Z a series of g-factor measurements of even Kr isotopes[2] in order to study the collective versus single particle nature of the 2_1^+ state. This experiment was completed in 2003 and will be discussed in the following article.

Batch mode processes have been used in the past to produce radioactive ion beams with medium to long half-lives. At LBNL, the BEARS project coupled two cyclotrons – the BIF (Biomedical Isotope Facility) for production and the 88-Inch Cyclotron for re-acceleration – to successfully run experiments with beams of ^{11}C ($T_{1/2}$ = 20 m) and ^{14}O ($T_{1/2}$ = 70 s). BIF is limited to proton beams at Ep ≤ 12 MeV; however, the longer half-lives of gaseous species, a similar technique can be used, but with the production and re-acceleration stages both utilizing the 88-Inch Cyclotron. We have dubbed this technique the Recyclotron method. For ^{76}Kr ($T_{1/2}$ = 14.8h) the four phases of the Recyclotron method – production, transfer, ionization and acceleration – were individually developed and optimized over the course of a few years of R&D and are discussed below.

The ^{76}Kr was produced using the ^{74}Se(α,2n)^{76}Kr reaction at 61 MeV (resulting in 38 MeV in the front of the Se). This reaction and energy was carefully chosen (using PACE calculations confirmed by measurements) to maximize the production of the desired Kr isotope while staying below the threshold for the reactions producing A = 75 products, which decay to the long-lived ($T_{1/2}$ = 120 d) ^{75}Se, a potential contaminant of the ion source. Much work went into the design of a water-cooled, thin target of the enriched isotope ^{74}Se, which had to be kept below the melting point of the selenium (221C) during bombardment with up to 12 pμA of alpha particles (depositing > 700 Watts in the target). The total production time was chosen to be about one half-life, or 16 hours.

After the production period, the selenium was melted. Over a period of an hour, the krypton gas diffused into a helium gas flow through a 30 meter long polyethylene line out of the production cave where it was trapped in activated charcoal in a liquid nitrogen bath. The gas transfer was monitored by ionization chambers located at various points along the transfer line. The peak transfer is approximately 30 mR/hour, corresponding to 4 x 10^{13} ^{76}Kr nuclei. This is about 10% of the production expected from PACE calculations. Because we are not able to make a direct measurement of the number of ^{76}Kr atoms being produced in the target (due to high activity and numerous sources of background radiation), it is not clear whether the discrepancy is due to ^{76}Kr not being produced at the expected rate or to the ions are not being efficiently transferred out of the target.

After the krypton transfer is complete, all remaining background gas is pumped out of the trap, then it is warmed up and the krypton slowly released into the Advanced Electron Cyclotron Resonance Ion Source (AECR). The efficiency for ionization of the Kr into charge state +15 is 13.5%, measured using a calibrated leak of stable krypton. The +15 charge state is used because the ionization is the highest and because ^{76}Kr^{+15} has nearly the same charge-to-mass ratio as ^{86}Kr^{+17}, a stable "analog" beam which is used to tune the ion source, cyclotron and beam line while the transfer is taking place. The measured combined efficiency for ionization and acceleration is 1-2%, consistent with the expected 13% AECR-U ionization efficiency for charge state +15 and a ≈15% cyclotron transmission efficiency.

The ^{76}Kr was delivered to the target over a period of approximately two hours. Typically, the beam current increased approximately linearly with time over the first hour as the ion source stabilized. The peak current of 3 x 10^8 particles/sec was stable for approximately 15 minutes then began to decrease over the next 30-60 minutes. The transmission from the cyclotron to the target was 50%, giving an average beam on target of 4(2) x 10^7 particles per second for two hours and a total of 3(1) x 10^{11} ^{76}Kr atoms on target per 24 hour batch cycle.

Table 1 shows the average efficiency at the various stages of the process during the g-factor experiment to be discussed in the following article, in which three production cycles occured in a 5-day run. Based on these efficiencies, the technique can be used to produce other gaseous radioactive beams with half-lives as short as 2.5 hours.

Table 1. Average production numbers for two batches

Production Period (hours)	16
Average ^{4}He current (pμA)	5.8(5)
Atoms of ^{76}Kr (PACE)	3.3(3) x 10^{14}
Atoms of ^{76}Kr in trap	3.9(9)x10^{13}
Production Efficiency[a] (%)	12(3)
Atoms of ^{76}Kr through cyclotron	7(2)x10^{11}
AECR +Cyclotron Efficiency[b](%)	1.8(7)

[a] Trapped atoms/Produced atoms (PACE)

[b] Accelerated atoms/Trapped atoms

REFERENCES

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